# THE ATMOSPHERIC TIDES AT WAKE ISLAND

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## ABSTRACT

Twelve years of hourly surface observations from Wake Island are analyzed to isolate the atmospheric tides and to study possible relations between the tides and weather over a very small land mass. In addition to determining the solar diurnal and the solar semidiurnal variation of temperature and pressure, the study demonstrates that the lunar semidiurnal pressure oscillation can be satisfactorily determined while the lunar semidiurnal temperature variation cannot be isolated with 12 years of hourly observations. The frequency of occurrence of precipitation shows only a slight suggestion of a lunar tidal period; however, the lunar semidiurnal precipitation component has the same relation to the lunar semidiurnal pressure wave as the solar semidiurnal precipitation wave has to the solar semidiurnal pressure wave. There is some evidence for a solar semidiurnal variation of cloudiness and a relationship between cloudiness and the semidiurnal pressure wave rather than between cloudiness and the predominantly diurnal temperature wave. A pronounced observational bias in sky cover associated with the moon's position makes it impossible to conduct any valid study of the relationship between sky cover and the lunar tidal period.

## 1. INTRODUCTION

Both the descriptive and theoretical aspects of the atmospheric tides have been studied extensively for nearly 200 years (cf. [8]). It was recognized that these variations are of larger amplitude in the Tropics and are more easily studied at these latitudes where synoptic pressure disturbances are generally small and infrequent.

The solar semidiurnal component of the atmospheric tides has received the most concentrated attention and its description in terms of the semidiurnal pressure variations is fairly well documented [2, 5, 9]. The diurnal oscillation is generally less pronounced and more susceptible to local influences. The moon also produces a tide in the earth's atmosphere, which has been well determined at many stations [1, 4]. The pressure variation by which the lunar atmospheric tide is detected is likely to be accompanied by a similar variation in temperature. Although the lunar tidal variations are small, their study contributes to our understanding of the atmosphere's dynamics.

The primary objective of this investigation is to study the variations of temperature, pressure, sky cover, and precipitation over a very small tropical island as functions of the solar and lunar days. Wake Island (fig. 1) was selected for this study for several reasons: it is representative of a small flat tropical island far removed from other land; it has a persistent wind regime throughout the year; and it has a continuous record of hourly surface observations for a period of 12 yr. beginning in November 1949.

## 2. DATA AND ANALYSIS

Data for the study were taken from punch cards supplied by the National Weather Records Center, Ashe-
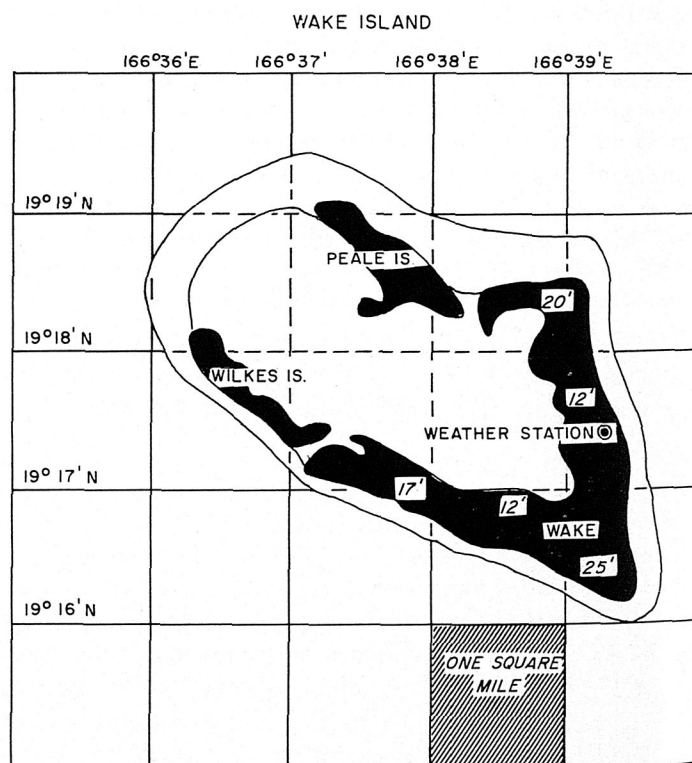


FIGURE 1.—Outline map of Wake Island. Dark areas depict dry land, clear outlines show outer margins of the barrier reef.
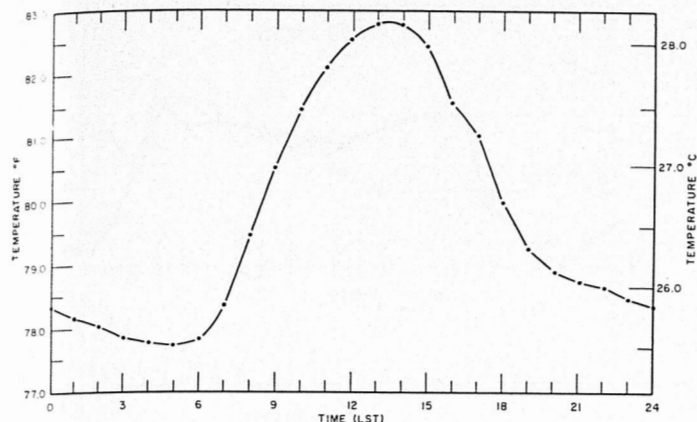
FIGURE 2.—The daily variation of temperature for the years 1950–1961.



FIGURE 3.—The daily variation of pressure for the years 1950–1961.

ville, N.C. Editing of the raw data was done by computing the standard deviation for each hour of the day for station pressure and surface temperature. Hourly changes were also computed and those that exceeded a critical value were examined individually and either deleted or corrected. The record is continuous except for several days in September 1952 when a typhoon interrupted observations.

The 12-yr. period was divided into two 6-yr. periods and each set was independently reduced in order to obtain an estimate of sampling effects. Harmonic components for frequencies 1, 2, and 3 cycles per day (solar or lunar) were determined for the two sets of years and the analysis of variance was performed to determine whether the mean amplitude of each of these harmonic components differed significantly from zero. The probable errors, P.E., were computed for the mean amplitudes of the frequencies 1, 2, and 3 for the 12-yr. period. Although
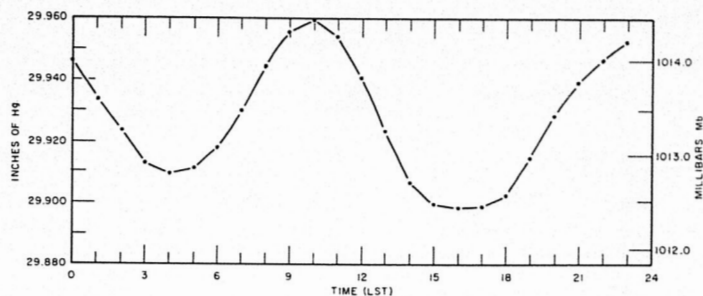
the use of the probable error is declining and it is not used in modern statistical practices [11], it is presented here as a basis for comparison with the results given in previous papers [1, 2, 3, 4].

## 3. DAILY VARIATIONS (SOLAR)

The mean hourly surface temperature (°F.) and station pressure (in. of Hg) values were computed with the results converted to °C. and millibars. The predominantly diurnal temperature wave and the semidiurnal nature of the surface pressure wave respectively, are clearly demonstrated by the curves of figure 2 and figure 3. The amplitude of the pressure wave is expressed in microbars (1 $\mu$bar=$10^{-3}$ mb.).

The time of maximum and the amplitude of this variation were determined by harmonic analysis [7] for frequencies 1, 2 and 3, which determine respectively, the 24-hr., 12-hr. and 8-hr. waves. The harmonic components can be expressed in the form

$$\hat{Y}_T = C_n \cos\left[\frac{360n}{P}(T-T_n)\right] = C_n \cos\left[\frac{360nT}{P} - \epsilon_n\right]$$

TABLE 1.—*The harmonic components of the solar diurnal variations and the lunar tidal variations of temperature, pressure, sky cover, and precipitation occurrence, for Wake Island, 1950–1961. The level of significance is indicated by asterisks. Absence of an asterisk indicates the results are not significant. Probable errors are given for comparison*

| | Freq. | TEMPERATURE | | | | PRESSURE | | | | SKY COVER | | | | OCCURRENCE OF PRECIPITATION | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Amplitude | Probable error (P.E.) | Phase | Time of maximum | Amplitude | Probable error (P.E.) | Phase | Time of maximum | Amplitude | Probable error (P.E.) | Phase | Time of maximum | Amplitude | Probable error (P.E.) | Phase | Time of maximum |
| Units | Cycles per solar day | °C. | °C. | Degrees | Hour | $\mu$ Bar | $\mu$ Bar | Degrees | Hour | Tenths sky cover | Tenths sky cover | Deg. | Hour | Relative percentage | Relative percentage | Deg. | Hour |
| Solar | 1 | ***1.3283 | 0.3216 | 205.0 | 13.7 | **289 | 76 | 60.5 | 4.0 | **0.446 | 0.1499 | 182.0 | 12.4 | ***0.82 | 0.21 | 58.4 | 3.9 |
| | 2 | **0.4433 | 0.1404 | 21.0 | 0.7 | **775 | 205 | 304.4 | 10.2 | **0.211 | 0.0614 | 185.0 | 6.2 | 0.32 | 0.17 | 127.3 | 4.2 |
| | 3 | 0.0472 | 0.0205 | 33.0 | 0.7 | **139 | 45 | 352.5 | 7.8 | 0.112 | 0.0729 | 32.4 | 0.7 | 0.06 | 0.06 | 113.1 | 2.5 |
| Units | Cycles per lunar day | °C. | °C. | Degrees | Class | $\mu$ Bar | $\mu$ Bar | Degrees | Class | | | | | Relative percentage | Relative percentage | Deg. | Class |
| Lunar | 1 | 0.0128 | 0.0059 | 226.8 | 15.1 | 6.0 | 13.0 | 257.9 | 17.2 | | | | | *0.22 | 0.08 | 5.5 | 0.4 |
| | 2 | 0.0050 | 0.0048 | 104.0 | 3.5 | **64.0 | 18.0 | 11.5 | 0.4 | | | | | 0.19 | 0.11 | 294.0 | 9.8 |
| | 3 | 0.0100 | 0.0057 | 236.7 | 5.3 | **8.0 | 2.0 | 15.0 | 0.3 | | | | | 0.16 | 0.13 | 107.2 | 2.4 |

***1 percent level of significance.
**5 percent.
*10 percent.

TABLE 2.—*Test of significance of the harmonic components of sky cover for frequency 2*

| Source of variation | Degrees of freedom | Sum of squares | Mean square | F ratio |
|---|---|---|---|---|
| Between groups | 2 | 8884622.0 | 4442311.0 | *F = 47.0 |
| Within groups | 2 | 189124.0 | 94562.0 | |
| Total | 4 | 9073746.0 | | |

*For the 1 percent level of significance, the required F is 99; for the 5-percent level, 19.

where $C_n$ is the amplitude of the $n$th harmonic, $T_n$ is the time, $\epsilon_n$ is the phase angle in degrees at which the $n$th harmonic has a maximum, and $P$ is the fundamental period, or total period of the periodic function. The results of the harmonic analysis appear in the top half of table 1 along with the results of the analysis of the other variables. The levels of significance indicated in table 1 were obtained from an analysis of variance, an example of which appears in table 2.

The mean hourly amount (in tenths of total amount) of sky cover was computed for the two sets of years, with the results shown in figure 4. It is clear that the results for the two independent periods are in good agreement. The amplitudes of the sine and cosine terms for frequencies 1, 2, and 3 were determined for the two sets of years and appear in figure 5 plotted in polar coordinate form. The results of the harmonic analysis appear in table 1.

The hourly observations of the occurrence of precipitation were coded in binary form (1, 0), i.e., rain or no rain. Then the total frequency for each hour of the day was computed and expressed as a percentage of the total number of cases. The results appear in figure 6. Figure 7 shows the amplitude and phase of the harmonic components for frequencies 1, 2, and 3 for the two sets of years. The results of the harmonic analysis appear in table 1.

## 4. THE LUNAR TIDAL VARIATIONS

The lunar day, which is about 24.81 solar hours, was divided into 24 classes and the hourly observations were summarized according to the particular class in which they belong. The times of upper and lower lunar transit are respectively class 12 and class 0.

The pressure variations by which the lunar tide is detected are likely to be accompanied by variations of temperature. The magnitude of these depends upon the readiness with which heat can be exchanged between regions of compression and rarefaction, or across the atmosphere's boundaries. Chapman [3] has shown that the horizontal heat flow directed between these regions is negligible. Thus the pressure variations are in all probability adiabatic, and the temperature variations nearly equal to the adiabatic value inferred from the known atmospheric tide.

An attempt was made to determine with the 12+ years of data the lunar semidiurnal temperature variation
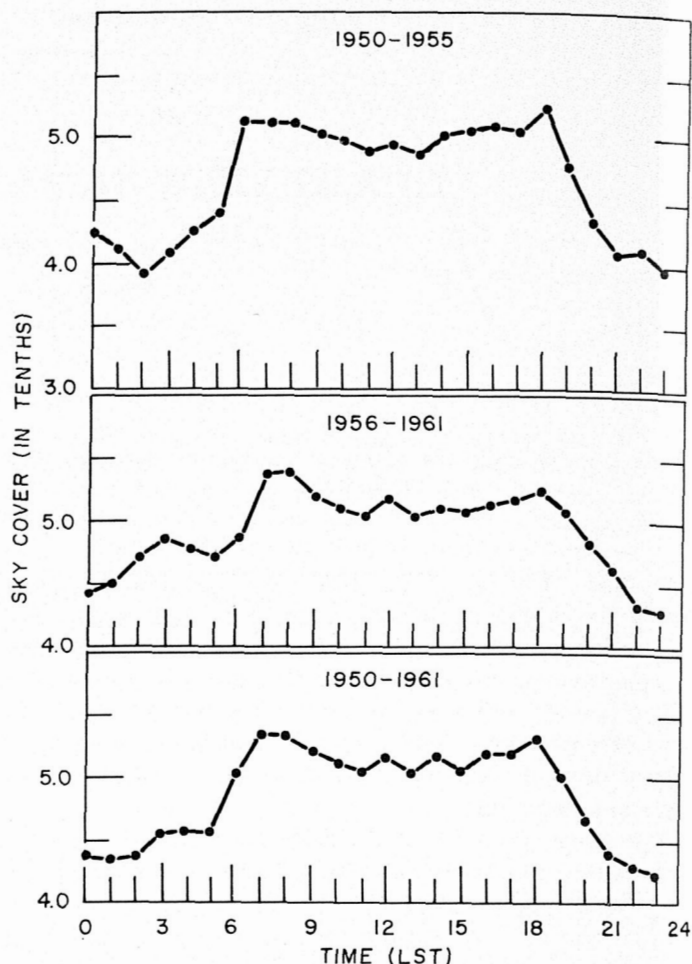


FIGURE 4.—The daily variation of cloudiness for the two 6-yr. periods and the total for the 12 years.
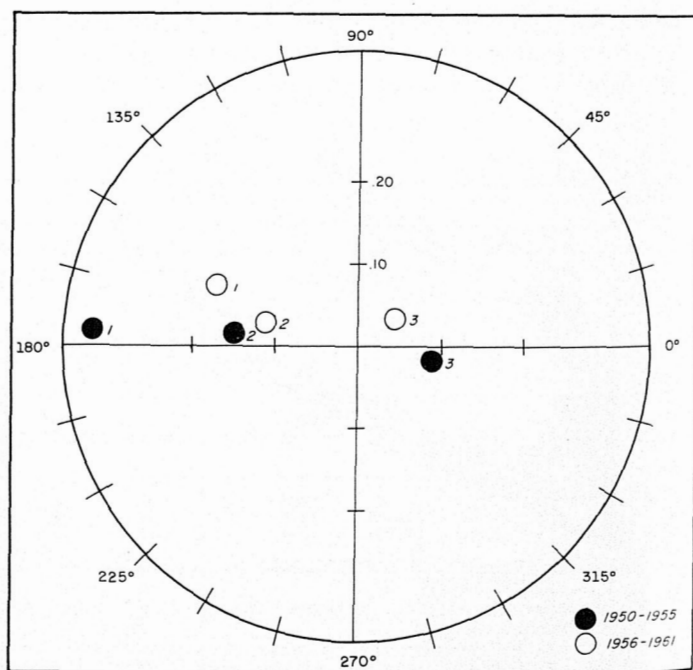


FIGURE 5.—Mean values of the amplitudes and phase angles of cloudiness for the two 6-yr. periods for the frequencies 1, 2, and 3 relative to the solar day. Amplitude scale in tenths of cloudiness.
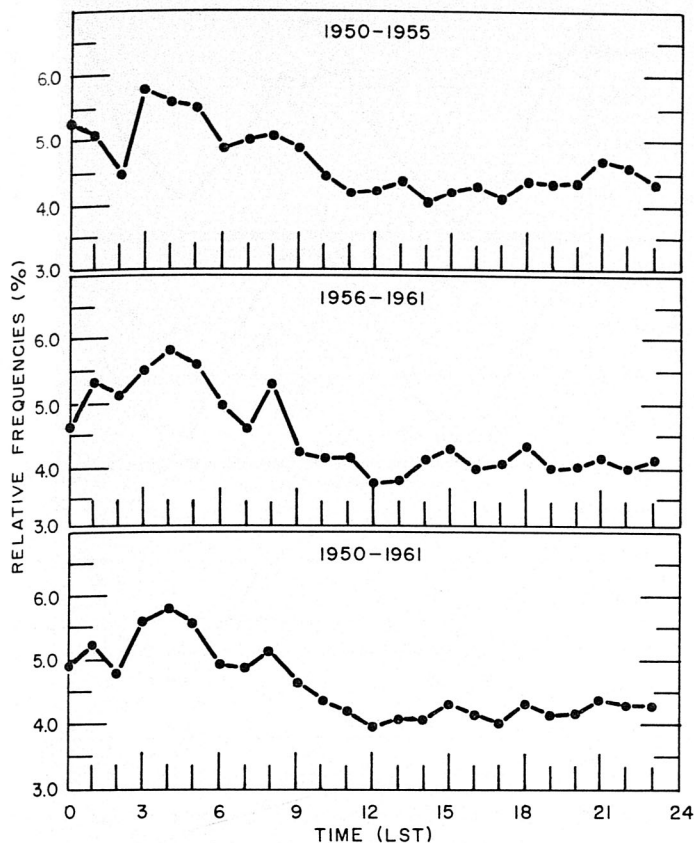
FIGURE 6.—The daily variation of the occurrence of precipitation for the two 6-yr. periods and the total for the 12 years.
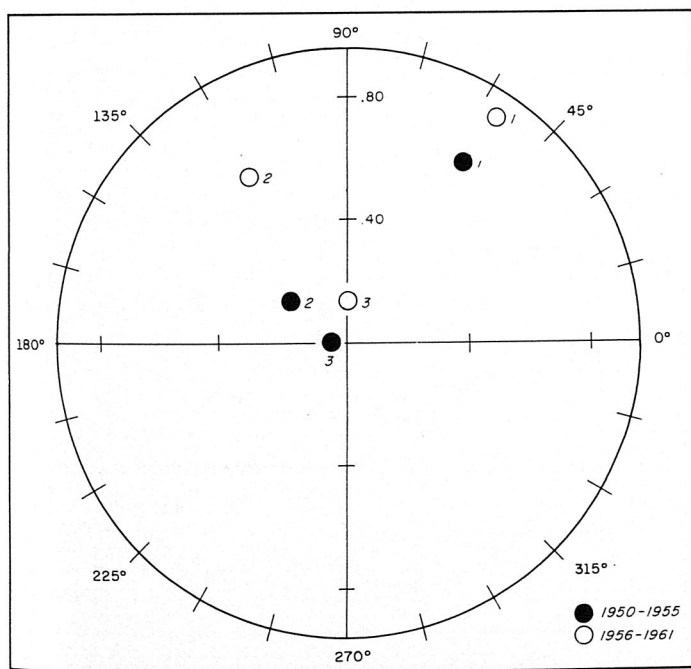
FIGURE 7.—Mean values of the amplitude and phase angles of the occurrence of precipitation for the two 6-yr. periods for the frequencies 1, 2, and 3 relative to the solar day. Amplitude scale expressed as relative percentage of occurrence.
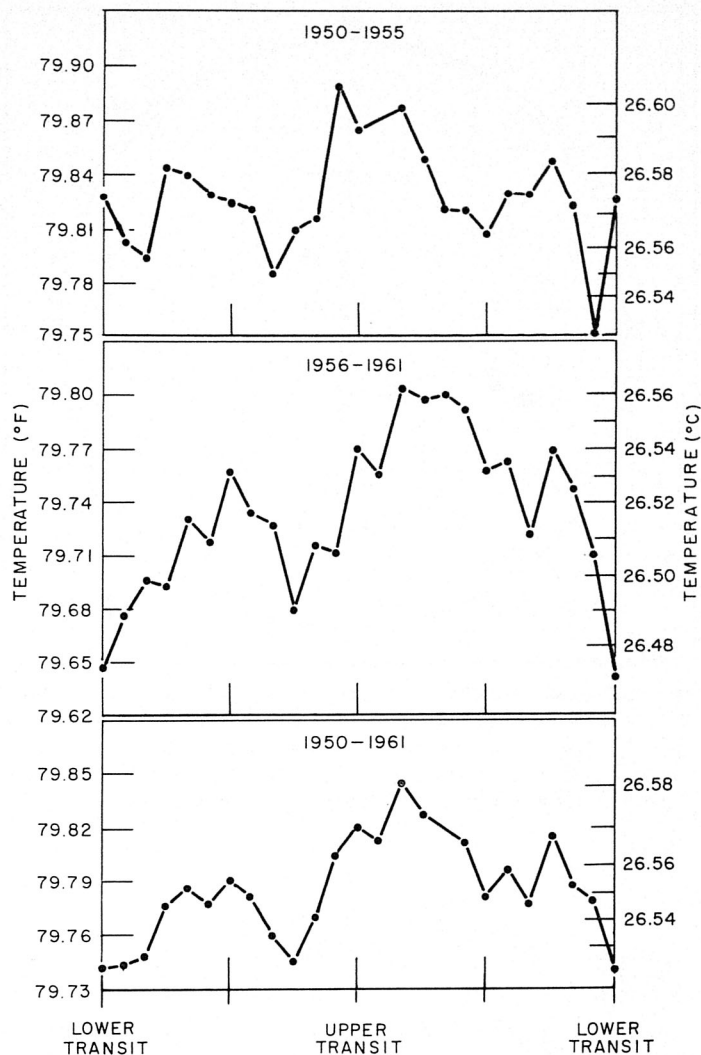
FIGURE 8.—The lunar tidal variation of temperature for the two 6-yr. periods and the total of the 12 years.

which, at best, is very small [3] (less than 0.01°C.). The results appearing in figure 8 show very little consistency between the two sets of years. The points shown in figure 9 indicate considerable scatter for each frequency and the analysis of variance showed the results to be not significant (see table 1).

As a control to determine random effects, another period close to the lunal tidal period was analyzed. The results from using this artificial period of 24.878 solar hours appear in figure 10 and show that the two sets of years have inconsistent variations comparable to those in figure 8.

The results of summarizing the pressure values according to the lunar period are shown by the curves of figure 11. The effect of the lunar semidiurnal tide is clearly demonstrated. Times of maximum pressure occur when the moon is at its upper and lower transit. The points shown in figure 12 clearly indicate the significance of frequency 2 (the 12.405-hr. wave). The results of the
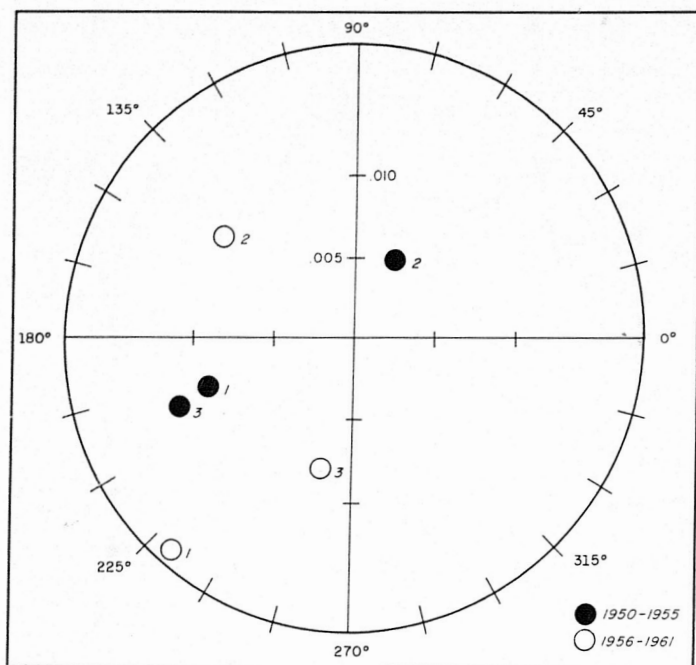
FIGURE 9.—Mean values of the amplitudes and phase angles of the lunar tidal variation of temperature for the two 6-yr. periods for the frequencies 1, 2, and 3 relative to the lunar day. Amplitude scale in °C. For frequency 2, the angles 0° and 180° are respectively the lower and upper transit of the Moon.
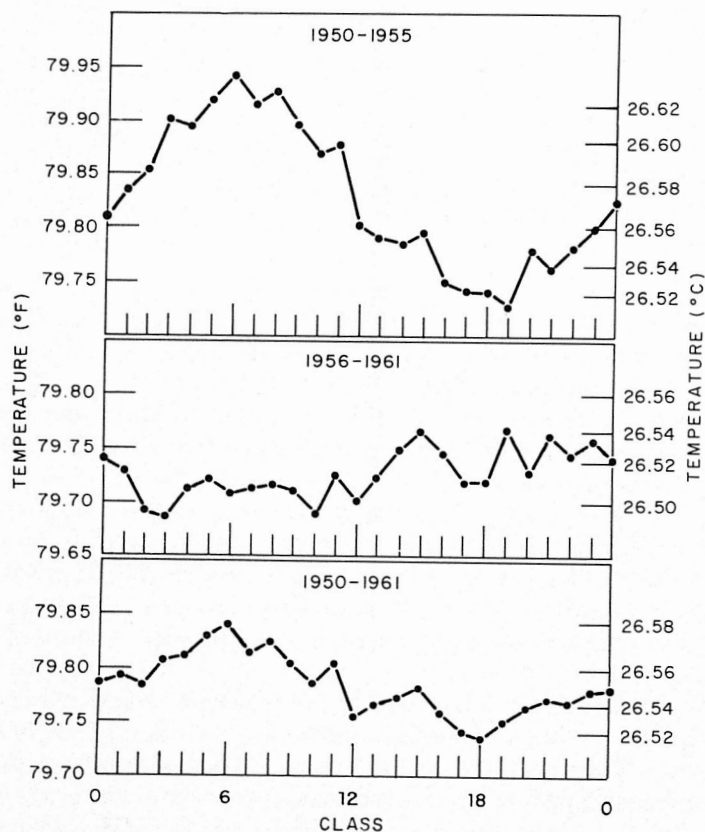
FIGURE 11.—The lunar tidal variation of pressure for the two 6-yr. groups and the total for the 12 years.

FIGURE 10.—The artificial period of 24.878 hr. for temperature for the two 6-yr. periods and the total for the 12 years.

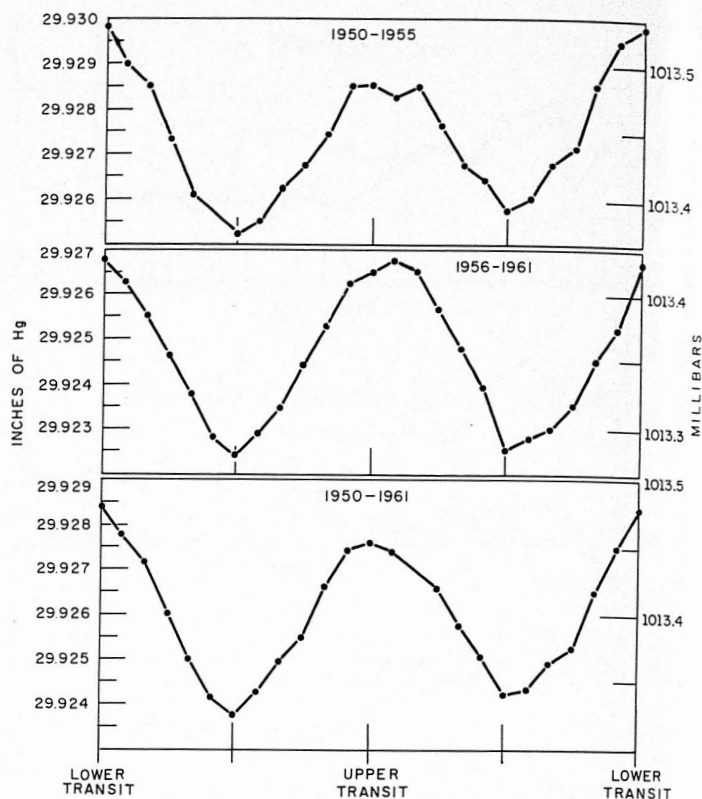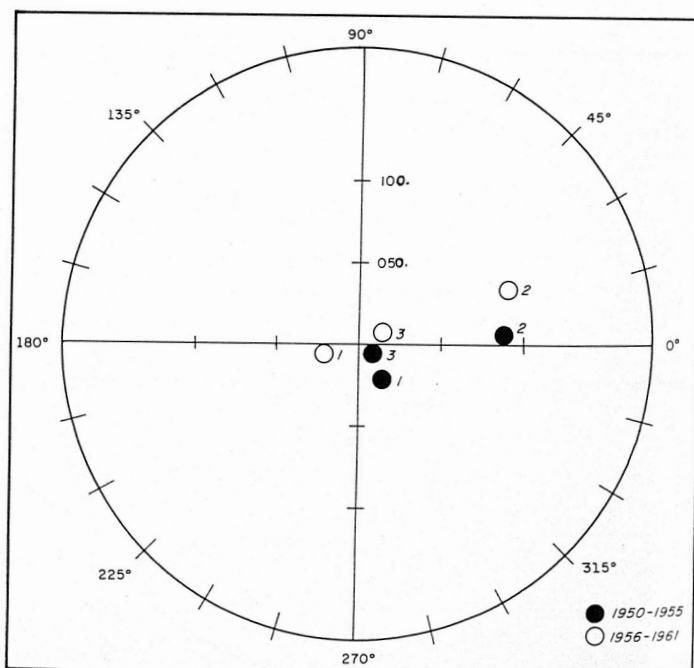FIGURE 12.—Mean values of the amplitudes and phase angles of the lunar tidal variation of pressure for the two 6-yr. periods for the frequencies 1, 2, and 3 relative to the lunar day. Amplitude scale in microbars. For frequency 2, the angles 0° and 180° are respectively the lower and upper transit of the Moon.
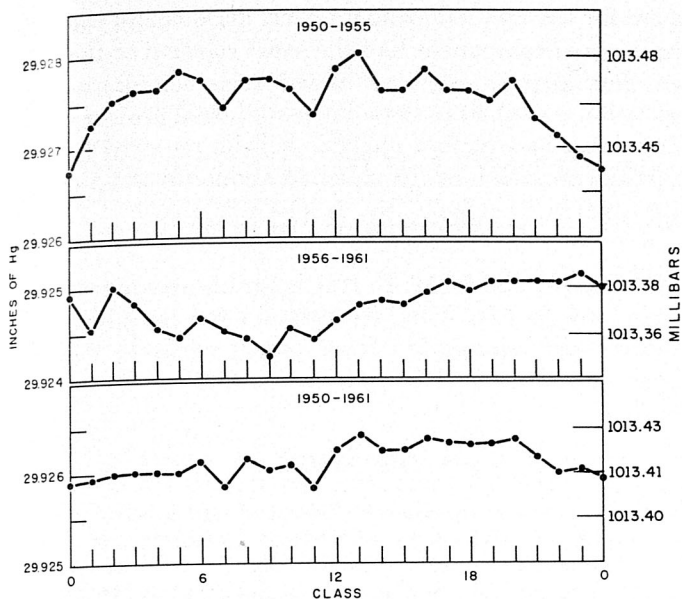
FIGURE 13.—The artificial period of 24.878 hr. for pressure for two 6-yr. periods and the total for the 12 years.
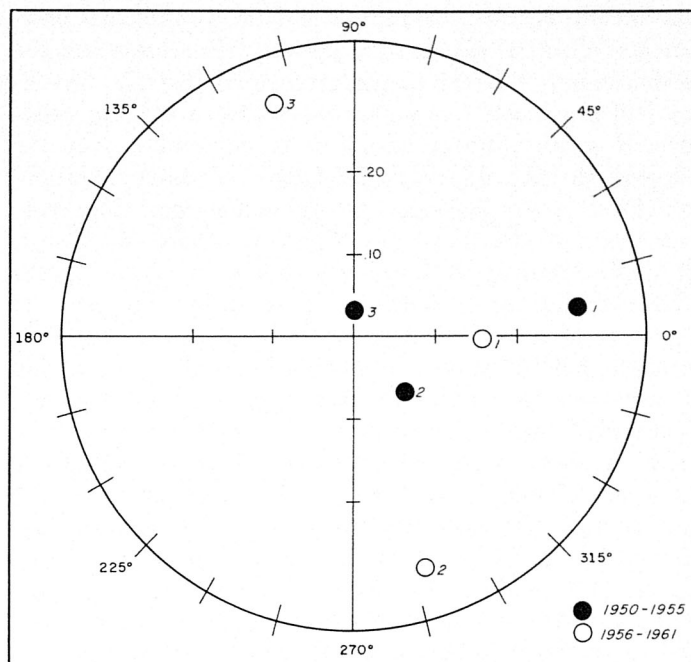


FIGURE 15.—Mean values of the amplitude and phase angles of the lunar tidal variation of the occurrence of precipitation for the two 6-yr. periods for the frequencies 1, 2, and 3 relative to the lunar day. Amplitude scale in relative percentage of occurrence. For frequency 2, the angles 0° and 180° are respectively the lower and upper transit of the Moon.
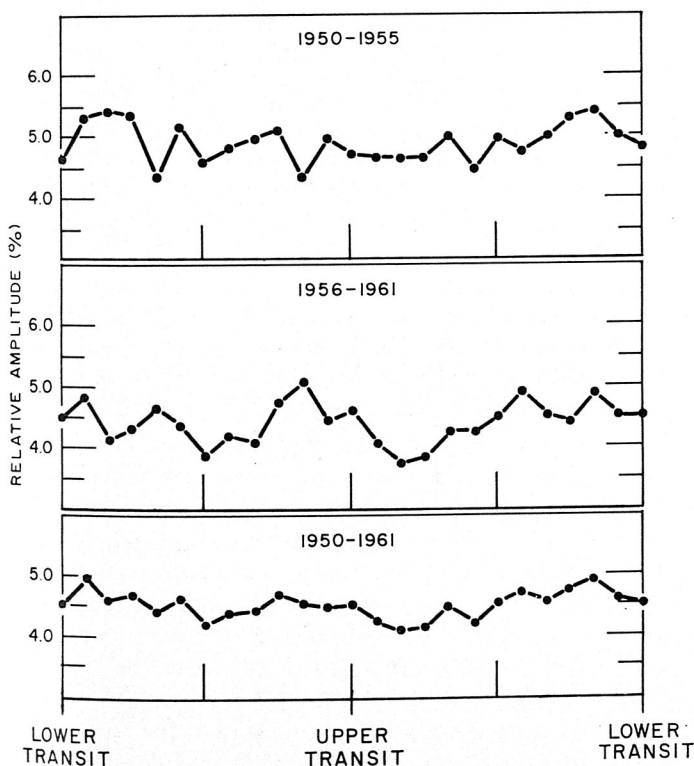


FIGURE 14.—The lunar tidal variation of the occurrence of precipitation for the two 6-yr. groups and their total.

harmonic analysis appear in table 1. The curves of figure 11 can be compared with the curves of an artificial period of 24.878 solar hours shown in figure 13.

The amount of sky cover was next analyzed to determine if there was any effect due to the lunar tidal action. Analysis of the data disclosed a significant increase in reported cloud cover with the moon overhead, but only during the night. This result indicated an observational bias in nighttime cloud observations and no further attempt was made to study the sky cover as a function of the lunar period.

The lunar variation of the hourly precipitation occurrence is shown by figure 14. These curves do not indicate a strong relationship between the two sets of years. The graph of figure 15 shows the harmonics for the two sets of years to be in phase but the amplitudes are not large. If there is any real effect, it is too complex or too small in amplitude to be determined from this sample of 12 yr. of data.

## 5. DISCUSSION

The diurnal temperature wave and the semidiurnal pressure wave were easily detected from 12 yr. of data. The results agree with what one would expect at this location.

There is considerable evidence ($P \leq 0.05$) for a semidiurnal variation of cloudiness with maximum amounts about 0700 and 1800 local time. This result suggests a

relationship between cloudiness and the semidiurnal pressure wave (fig. 3) rather than between cloudiness and the predominantly diurnal temperature wave (fig. 2). Sverdrup [10] previously has presented evidence for the existence of a semidiurnal variation in cloudiness over the tropical oceans with maximum amounts about 0600 and 1800 local time. This semidiurnal variation of cloudiness over tropical oceans has not been conclusively explained, although Sverdrup [10] suggests that it is related to the solar semidiurnal oscillation. This oscillation has the character of a wave that travels around the earth and is accompanied by converging winds in front of the region of maximum pressure and diverging winds in the rear; in any given locality, maximum convergence occurs twice daily, at about 0600 and 1800 local time, i.e., about the times when cloudiness over the tropical oceans reaches a maximum. Although the effect might be partially explained by local heating of the island, recent findings by Lavoie [6] would tend to argue against this. He found that a 14-fold increase in the exposed land surface between high and low tide failed to have any effect upon the amount of cloud cover at Eniwetok Atoll.

The rainfall shows evidence ($P \leq 0.01$) for a maximum around 0400 local time, presumably the result of instability and convection caused by radiational cooling of cloud and moist layers. The secondary maxima around 0800 and 1800 local time might be related to the variations in sky cover (fig. 4) and to the time of maximum convergence ahead of the semidiurnal pressure wave (fig. 3).

The effect of the lunar atmospheric tide on temperature was not detected. This variation is so small that one would not expect it to be detected with only 12 yr. of data. However, the lunar semidiurnal pressure wave was easily demonstrated, and the results were consistent with those shown previously, e.g., Ocean Island, Pacific Ocean, 0.9° S., 169.6° E., [4], with maximum pressure during the moon's upper and lower transit.

A pronounced observational bias on sky cover due to the light of the moon made it impossible to conduct any valid study of the relationship between sky cover and the lunar tidal period. The frequency of occurrence of precipitation showed only a slight suggestion of a lunar tidal period. However, both the lunar diurnal and the lunar semidiurnal components showed essentially the same phase for the two independent 6-yr. periods and the lunar semidiurnal component had the same relation to the lunar semidiurnal pressure wave as the solar semidiurnal precipitation wave had to the solar semidiurnal pressure wave. More data and further analysis will be required before a definite conclusion can be reached about this relationship.

## ACKNOWLEDGMENTS

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